Lecture No. 9

Particle Sources

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Lecture Outline

- **Electron Sources**
  - **Basic information. A brief review and some glossary.**
  - **How to extract electrons.**
  - **Characteristics of an electron source.**
  - **Examples of existing sources.**
  - **Performance limiting factors.**
  - **An example of a new source scheme.**
- **Protons and Heavy Ions Sources**
- **Anti-particles Sources**
- **Neutron Sources**

Electron Story

Discovered by
J.J. Thomson in 1897

For the first time it was proved that the atom is not indivisible and that is composed by more fundamental components.

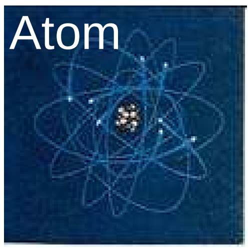
From the Greek ÈLEKTRON that means "Amber".

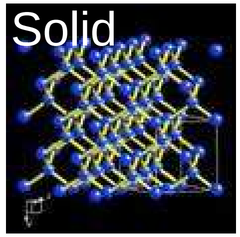
Fundamental particle: lightest lepton.

$m = 9.1095 \times 10^{-31}$ kg or 9.1095×10^{-28} g
(1837 times lighter than a proton)

$e = 1.6022 \times 10^{-19}$ C or 4.803×10^{-10} esu

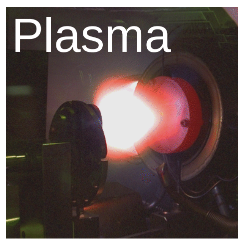
Where Electrons Can Be Found and Produced





Widely used in sources for: accelerators, microscopes, technological applications, ...

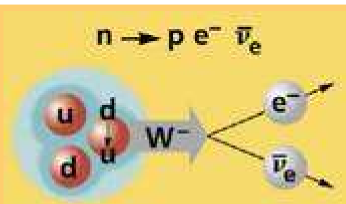
Low current, high quality beams, microscopes, electron holography, inverse photoemission, ...



Very high gradient accelerators research. Proton and heavy ions sources

Pair formation

Commonly used in positrons and anti-protons sources



Heavier Particle Decay Product

Radiation source

Two Families of Particles: Fermions and Bosons

• In quantum physics, all particles can be divided into two main categories according to their **spin**.

• Particles with half-integer spin are called **fermions**, those with integer spin are called **bosons**.

• Extremely important difference: only fermions, follow the **Pauli exclusion principle**:

•*"No two fermions may occupy the same state"*.

•As a consequence, when fermions are introduced into a system, they will occupy higher energy levels when the lower ones are filled up.

•On the contrary, bosons will all occupy the lower energy level allowed by the system

•Because of the Pauli principle, the two particle categories follow different energy distributions:

Bosons

$$f_{BE}(E) = \frac{1}{Ae^{E/kT} - 1}$$

Bose-Einstein Distribution: photons, mesons

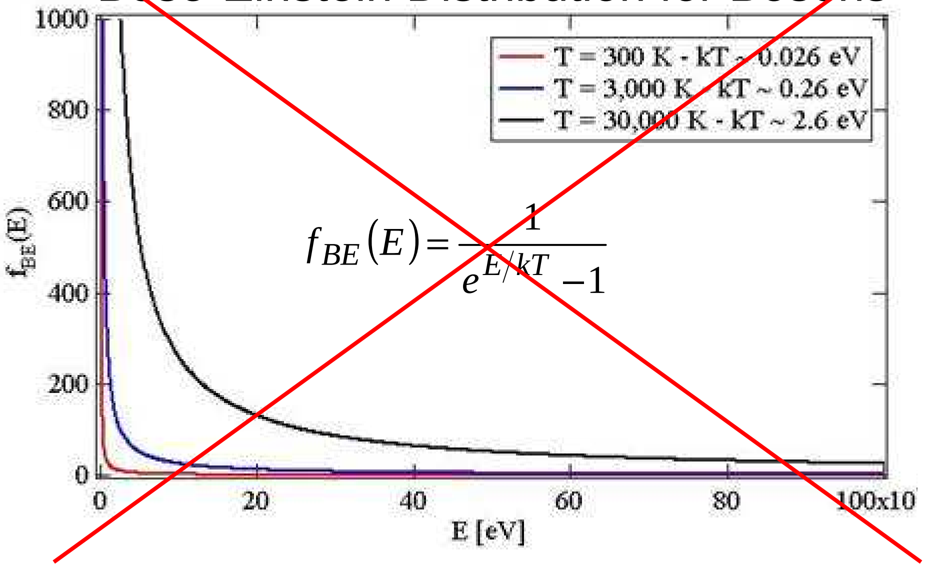
Fermions

$$f_{FD}(E) = \frac{1}{e^{(E - E_F)/kT} + 1}$$

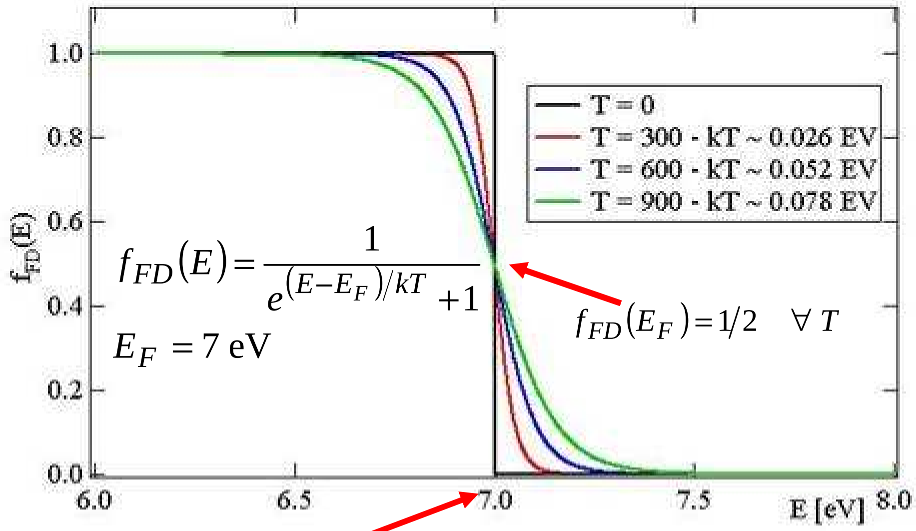
Fermi-Dirac Distribution: electrons, protons, neutrons,...

The Fermi Energy

~~Bose-Einstein Distribution for Bosons~~



Fermi-Dirac Distribution for Fermions

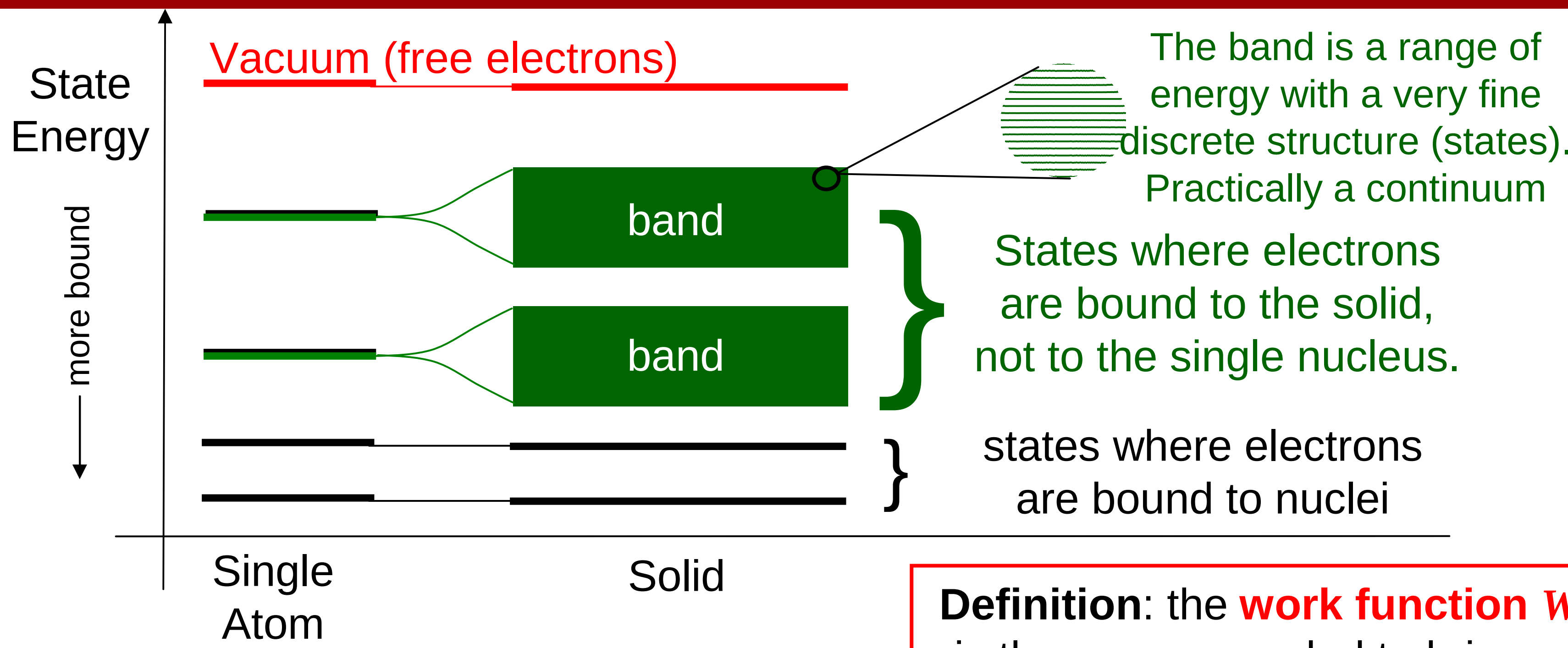


We will deal only with electron sources.
Being electrons fermions (spin 1/2)
we will concentrate our attention in the
Fermi-Dirac distribution

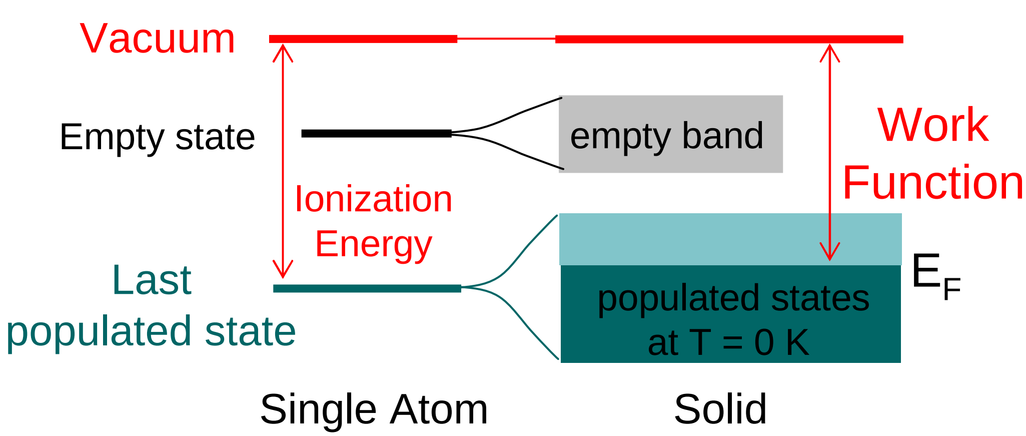
Definition : In a system of fermions the **Fermi energy E_F** is the energy of the highest occupied state at zero temperature.

We are interested to the case where the system of fermions is **a solid with its electrons**.
The E_F value is a property of the particular material. Example: E_F for copper is 7 eV.

Solids and Work Function



Definition: the **work function W_F** is the energy needed to bring an electron from the Fermi level to the vacuum level
(a point at infinite distance away outside the surface).



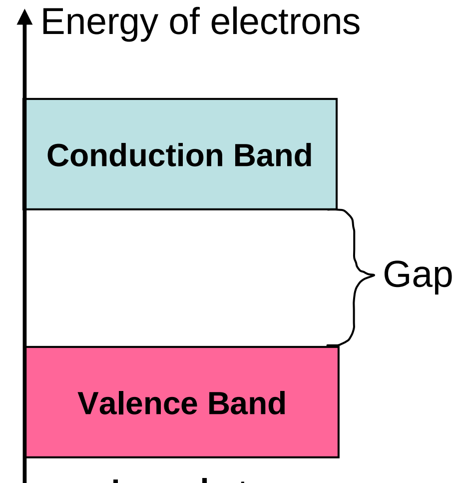
Example: for Copper (Cu)
E_I = 7.7 eV
W_F = 4.7 eV

Insulators and Conductors

Definition 1: In solids, the **valence band** is the band that at T = 0 K, is occupied by the highest energy electrons.

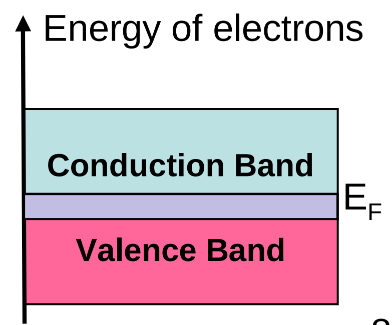
Definition 2: The **conduction band** is the higher energy band above the valence band.

INSULATORS. At T = 0 K:
- The valence and the conduction bands are separated by a **gap** with no allowed energy states.
- The valence band is completely filled with electrons.
- The conduction band is totally empty.



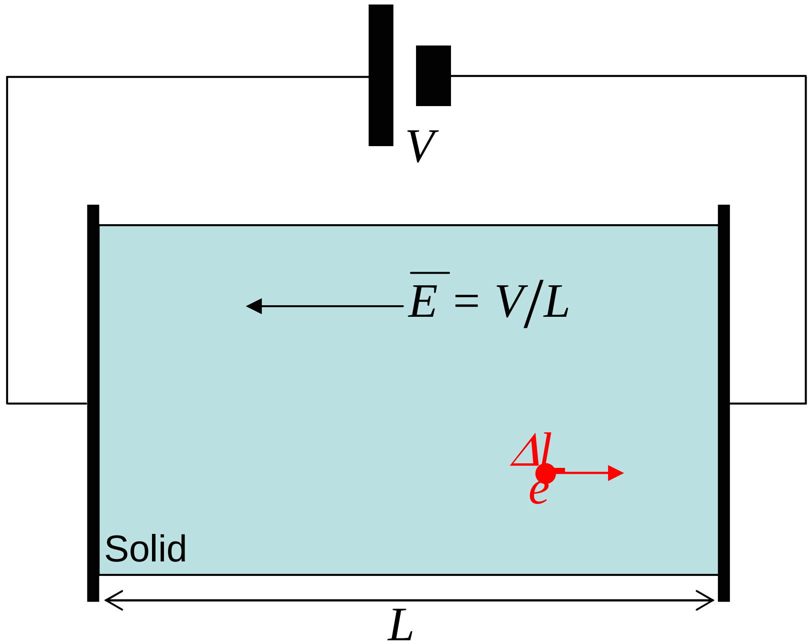
a. Insulator

CONDUCTORS. At T = 0 K:
- The valence and the conduction bands **overlap**. The same band is now at the same time of valence and of conduction.
- The energy states in such resulting band are only **partially filled**.

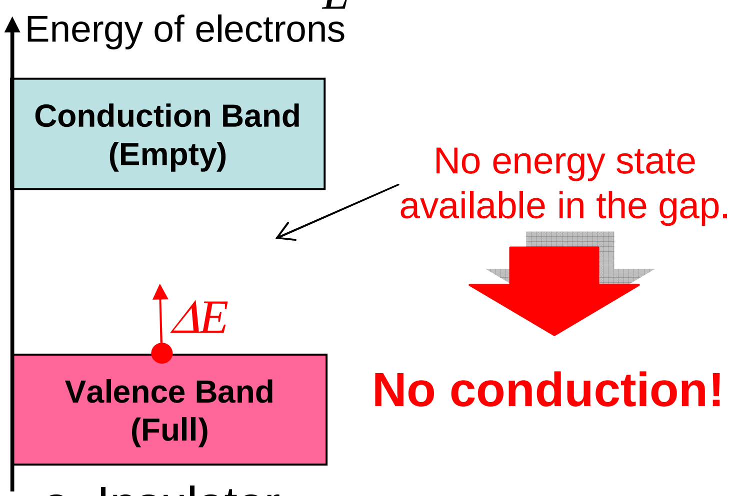


b. Conductor

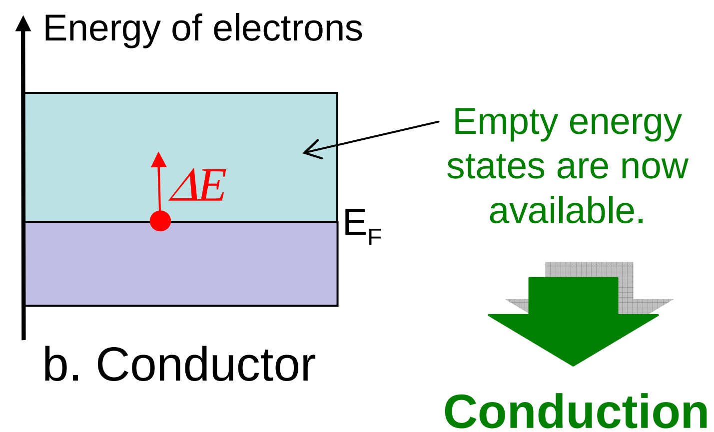
The Conduction Phenomenon



$$Energy\ Variation = \Delta E = \left|\overline{E}\right|\Delta l = \frac{V}{L}\Delta l$$



a. Insulator



b. Conductor

Semiconductors: a Special Kind Of Insulator

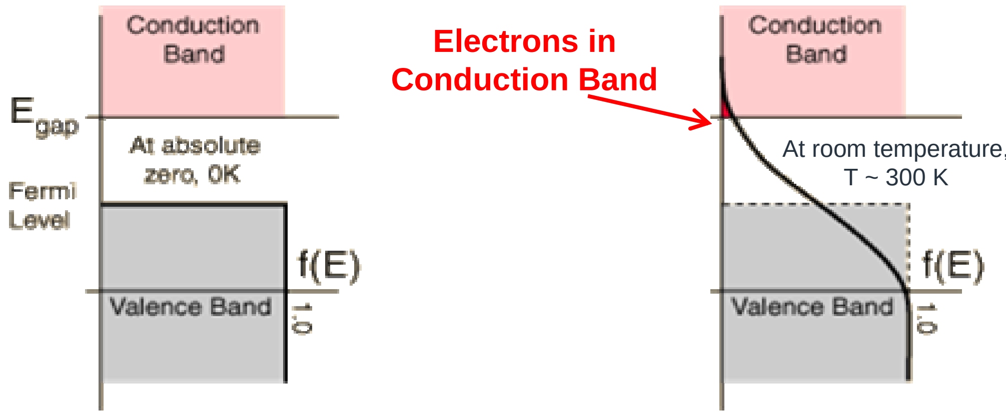
Above absolute zero (T = 0K), the atoms in a crystal (solid) start vibrating.

As a result, some electrons scatter with the atoms gaining extra energy (the larger is T, the larger is the extra energy).

For a high enough temperature, in some insulators this extra energy can be larger than the gap and electrons in the valence band are allowed to go in the conduction band.

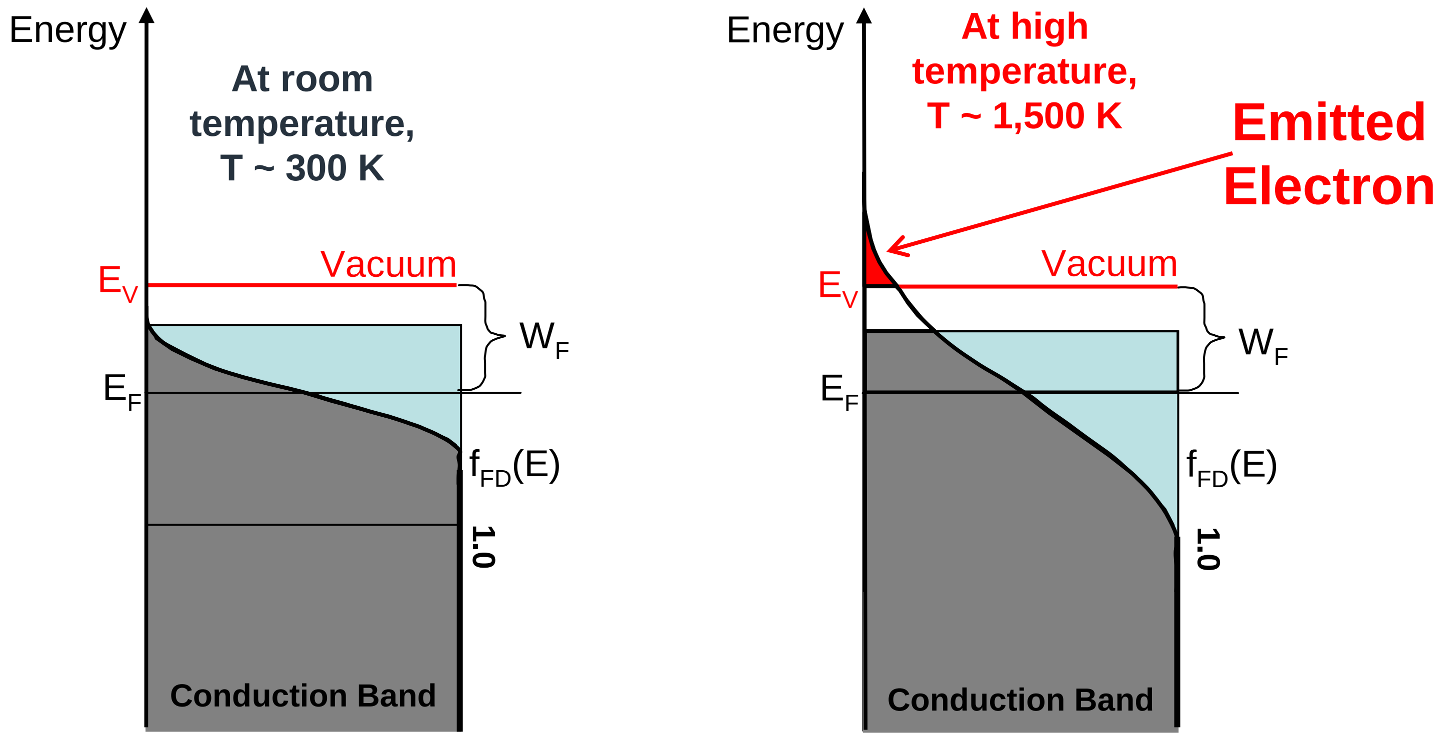
As a consequence, such a solid undergoes to a **phase transition from insulator to conductor** when the temperature is increased!

A semiconductor is an insulator with a relatively **small gap** between the valence and conduction bands.
The gap is small enough that at room temperature (T ~ 300K), such a phase transition has already happened.



Silicon,
Germanium,
….

Thermionic Emission in Conductors



Thermionic emission was initially reported in 1873 by Guthrie in Britain.

Owen Richardson received a Nobel prize in 1928 "for his work on the thermionic phenomenon and especially for the discovery of the law named after him".

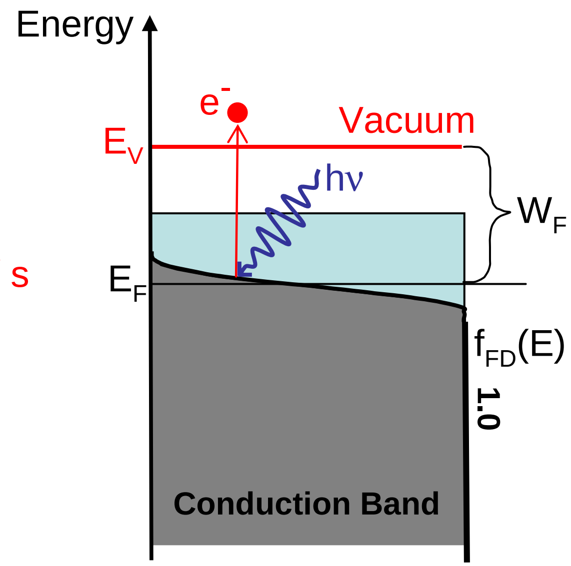
$$i = AT^{\frac{1}{2}}e^{-w/kT}$$

The Photoelectric Effect

$$\boxed{Photon\ Energy = E_{ph} = h\nu}$$

photon frequency

Planck Constant= 6.626068 × 10^{-34} m^2 kg / s



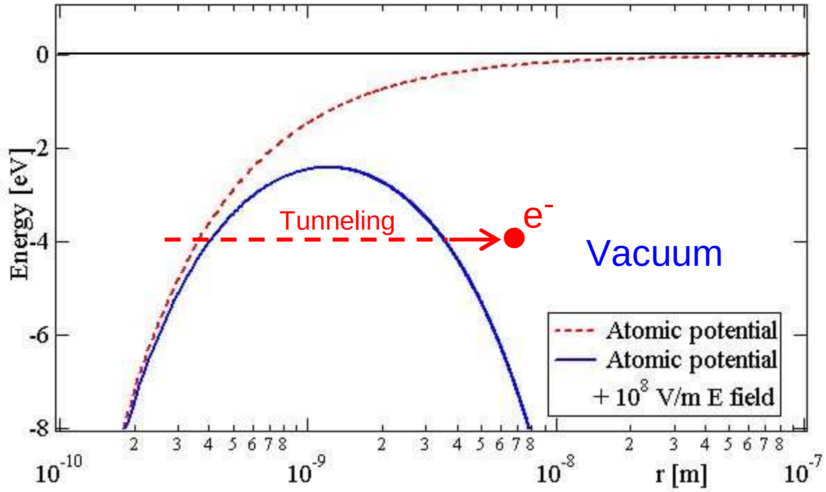
$$\boxed{If \quad E_{ph} \geq W_F}$$

$$\boxed{T_{e-} = E_{ph} - W_F}$$

Albert Einstein received the 1921 prize in 1922 for work that he did between 1905 and 1911 on the Photoelectric Effect.

Max Planck received the 1919 Nobel for the development of the Quantum Theory of the photon.

Field Emission



$$U_p = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r} - e\left|\overline{E}\right| r$$

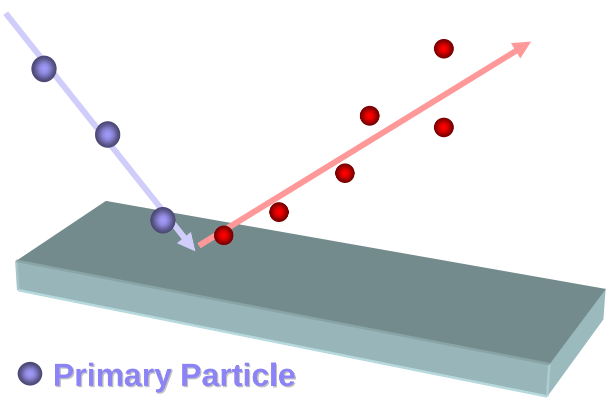
$$\left|\overline{E}\right| = \text{constant}$$

Quantum tunneling is the quantum-mechanical effect of transitioning through a classically-forbidden energy state.

Field emission was first observed in 1897 by Robert Williams Wood.

But only in 1928, Fowler and Nordheim gave the first theoretical description of the phenomenon. It was one of the first application of the quantum mechanics theory.

Secondary Emission



Primary Particles: photons, electrons, protons, neutrons, ions, ...

Physical Processes: ionization, elastic scattering, Auger Electrons, photoelectric effect, bremsstrahlung and pair formation, Compton scattering, ...

Electron Gun Schematic

Electron Generator → **Accelerating and Focusing Section** → **Application**

- Thermionic
- Photoelectric
- Field emission
- Secondary emission
- ....

Focusing: usually by stationary magnetic fields.

Acceleration: by electric fields.

- Electrostatic
- Pulsed
- Radio Frequency
- Wakefields

Pulsed, Radio Frequency: Higher gradients

Electron Source
Main Parameters

Energy: from few eV to several MeV
Energy Spread: from ~ 0.1 eV and up.

Current:

- Average: from pA to several tens of A.
- Peak: from μA to thousand of A.

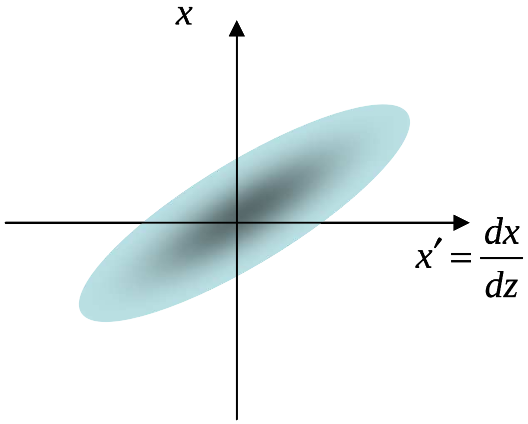
Time Structure:

DC
Pulsed: from single shot to hundreds of kHz
CW: from hundreds of MHz to several GHz

Pulse Length: from hundreds of fs to seconds.
Single electron.

Polarization: orientation of the electron spin

The Emittance: An Important Gun Parameter



Emittance: volume of the phase space occupied by the particles of the beam

Liouville Theorem: in a Hamiltonian system (non-dissipative system) the emittance is conserved

effective (rms) Emittance: $\varepsilon_{rms} = \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x\, x' \rangle^2}$

Smaller emittance are usually preferred.
It is very easy to increase the emittance, but very hard to decrease it!

Brightness and Degeneracy Factor

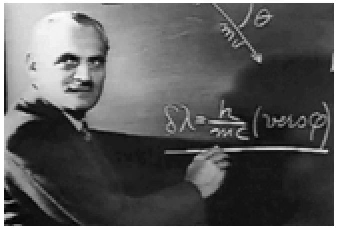
Brightness: phase space density of particles. I.e. number of particles per unit of phase space volume.

Heisenberg uncertainty principle: it is impossible to determine with precision and simultaneously, the position and the momentum of a particle. Applied to emittances:

$$\varepsilon_w \geq \lambda_c / 4\pi \qquad w = x, y, z$$

$$\lambda_c \equiv Compton\ wavelength = h/mc = 2.426\ pm\ \ for\ electrons$$

This can be interpreted as the fact that the phase space volume occupied by a particle is given by: **$(\lambda_c/2\pi)^3$ =** elementary phase space volume



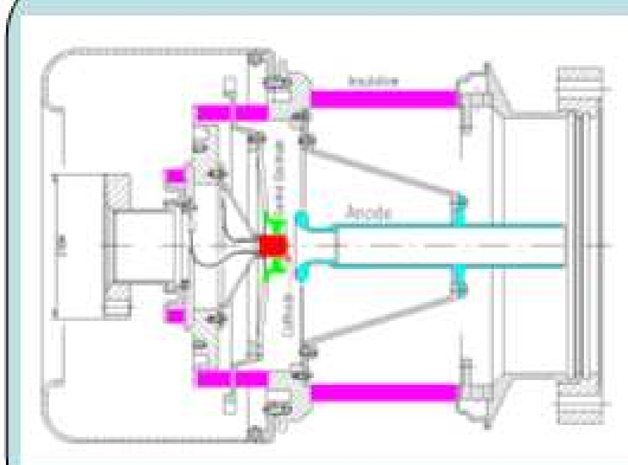
Degeneracy Factor, δ : brightness in units of elementary phase space volume. Number of particles per elementary volume.

Because of the Pauli exclusion principle the **limit value of δ** is: infinity for bosons and **1 for non polarized fermions**.

Short pulses, low energy spread, small emittances, high current densities, all lead to a **high degeneracy factor.**

Examples of Electron Guns

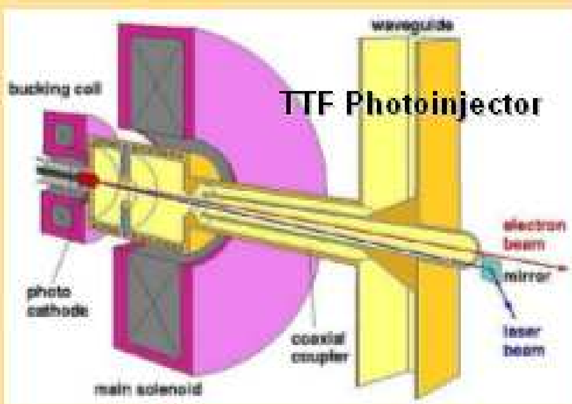
Thermionic Electron Gun



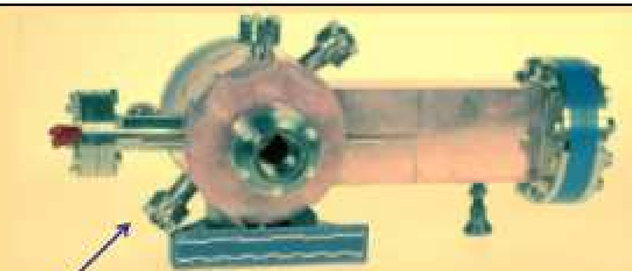
LINAC LAB Gun (Fermi Lab):
E = 10 keV
Current = 2 A max
Application: LINAC Injector

Charge densities
~ 10 A/cm²

RF Gun with Photocathode



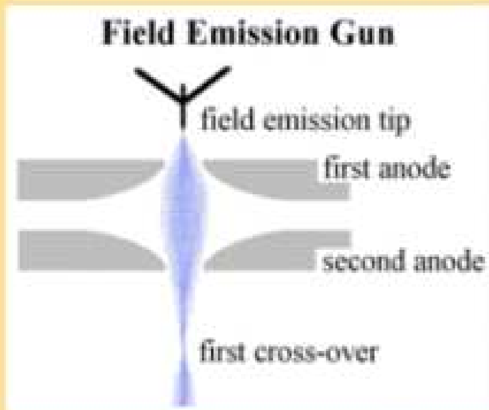
Charge densities up to 10^5 A/cm²

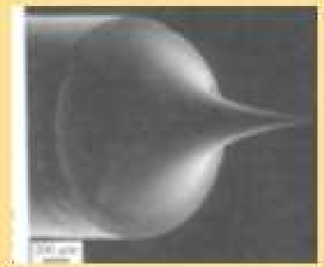


ATF (BNL) Gun III (LINAC Injector):
- Energy ~ 2 MeV
- Normalized rms emittance of 2.6 mm mrad
- Charge of 1 nC
- Pulse length of 10 ps
- RF = 2856 MHz (100 MV/m)

More Examples

Field Emission Electron Gun

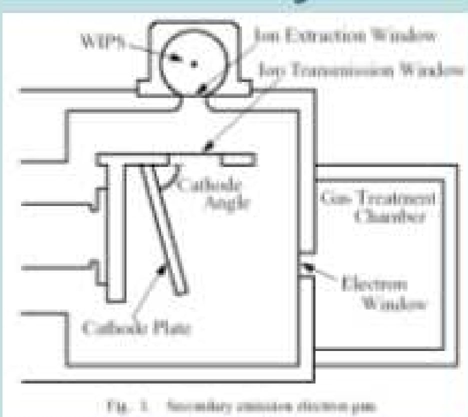


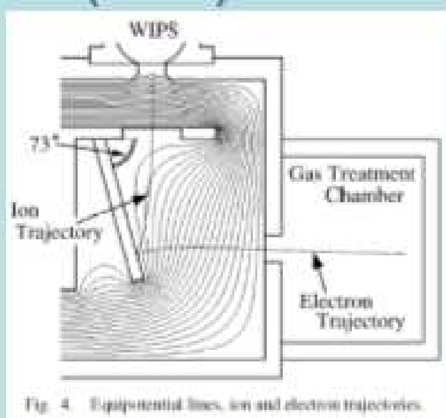


Charge densities up to 10^5 A/cm^2

THERMO Electro Corporation:
- Field at the cathode tip > 1 MV/cm
- 100 nm spot size at 5 nA sample current
- Current density ~ 50 A/cm^2
- Application: Electron microscope

A Secondary Emission (SEM) Source





E = 80 kV
Current density: 6.4 mA/cm^2
Ion source energy = 10 kV
Very compact
Application: gas treatment.

P.R Chalise et al., Jpn. J. Appl. Phys. 40, 1118 (2001)

Performances Limitations

High power thermionic guns.
- Average Current. Limits in the cathodes current density.
- Cathode lifetime.
- Cathode thermal emittance limit

RF Guns.
- Repetition Rate. Heat load in the RF structures limits.
- Max electric field. Field emission limits. Dark current.

Field emission guns.
- Max electric field at the tip. Limits in the minimum size of the tip.
- Intrinsic low average current.

Secondary Emission Gun.
- Low current densities.
- High energy spread.

The Ultimate Limit

Practically, most of the edge applications (accelerators, free electron lasers, microscopes, inverse photoemission, ...) are limited by the performance of the electron gun in:

- Emittance
- Energy spread
- Brightness

Degeneracy factor δ

- Thermionic: $\delta \sim 10^{-14}$
- SEM: $\delta \sim 10^{-14}$
- Photo-RF guns: $\delta \sim 10^{-12}$
- Field emission: $\delta \sim 10^{-5}$

The degeneracy factor inside a metal cathode is ~ 1 !!!

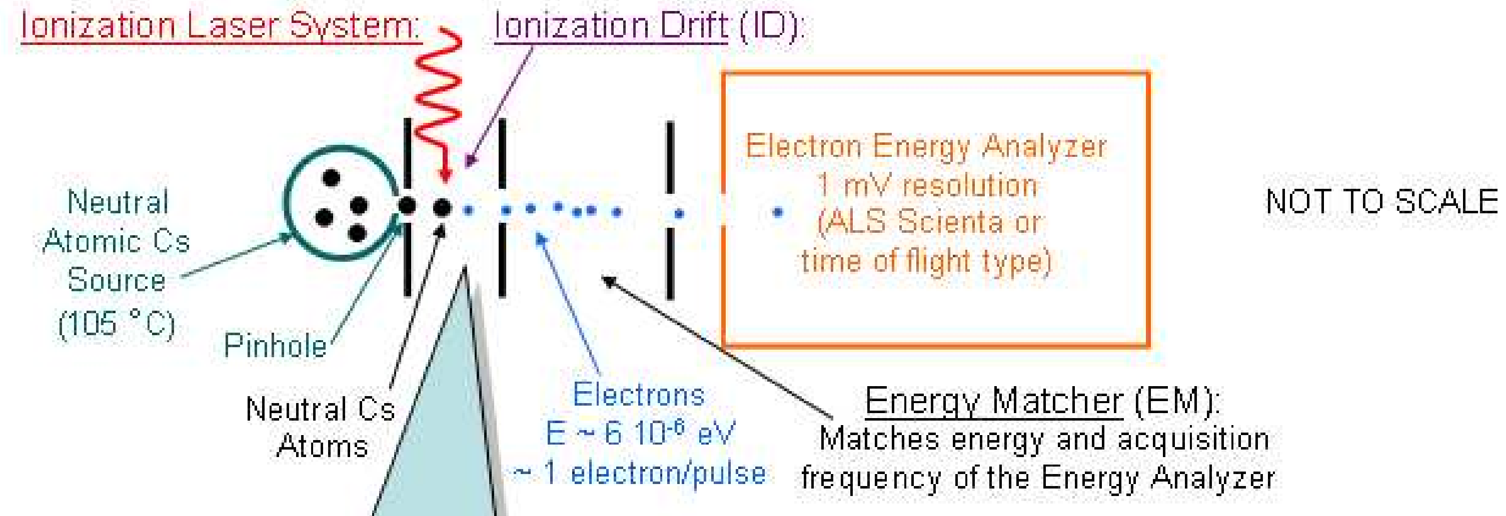
How do we loose all of that ?

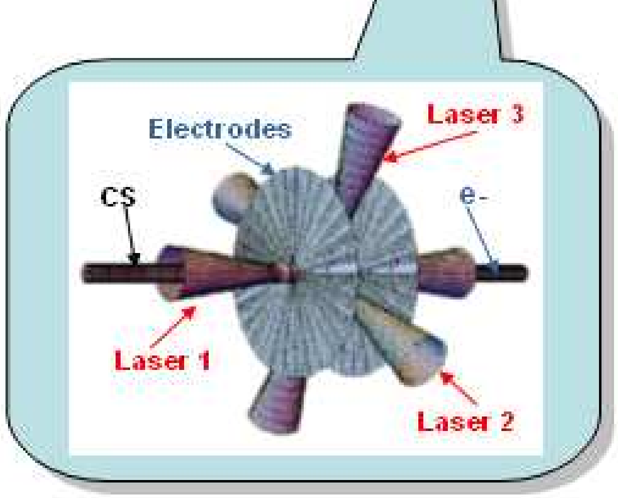
Extraction Mechanism

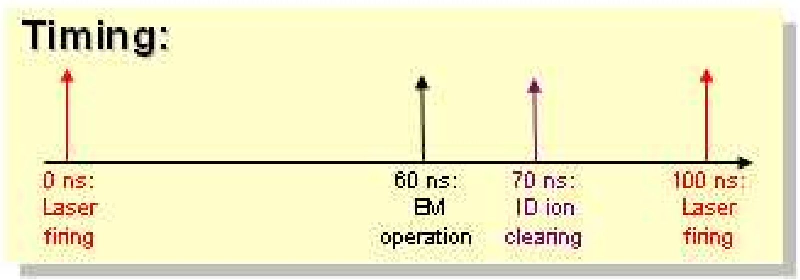
Coulomb interaction (space charge)

A High Degeneracy Electron Source

M. Zolotorev, E. D. Commins, P. Denes, Z. Hussein, G. Lebedev, S. Lidia, D. Robin, F. Sannibale, R. Schoenlein, R. Vogel, W. Wan.
(Lawrence Berkeley National Laboratory)







Fundamental Concepts

1) Electron Excitation. In the region of well defined and controlled volume (defined by the overlap of the lasers) we ionize on average one alkali atom per laser pulse. The electron in the excited atom will have a total energy close to zero and will start to drift away from the ion.

2) Waiting Period. After the laser pulse, we wait the time necessary for the electron to go far enough from the ion loosing most of its kinetic energy and we apply a short pulsed voltage to extract the electron from the ionization region.

3) Electron Acceleration. In this step, we accelerate the electron up to the energy required by the considered application.

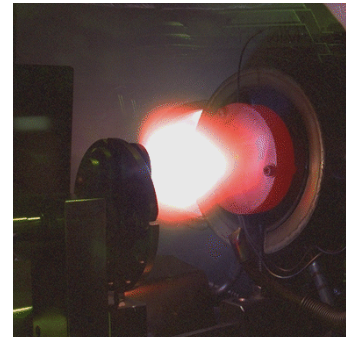
4) Ion Clearing. After the electron acceleration, we apply a “cleaning” field in order to remove the residual ion before the beginning of the following cycle. In this way it is avoided that the residual ion will interact with the electron produced in the next pulse.

The application of all such concepts allows to eliminate the Coulomb interaction between electrons (a single electron per cycle is produced) and to properly control the interaction between the electron and ions (parent and residual ones).

The degeneracy factor for this source is expected to be: $\delta \sim 10^{-2}$

Protons and Ions Sources

In most protons and ion sources a gas of neutral atoms or molecules is "heated" into a *plasma* state were ions and electrons are dissociated and move independently as free particles.



Heating mechanism can be of various kind: thermal, electrical, or light (ultraviolet light or intense visible light from a laser).

In a source, the ions are then extracted from the plasma and accelerated.

Neutral gas of practically any specie of atom can be produced and used in sources. For example, neutral gas of metals can be obtained by heating the solid element inside ovens

Discharge Based Ions Sources

In *Penning* discharge sources, *Magnetrons* and *Plasmatrons* a high voltage discharge (arc) in 0.001 to 1 Torr pressure is used for generating the plasma.

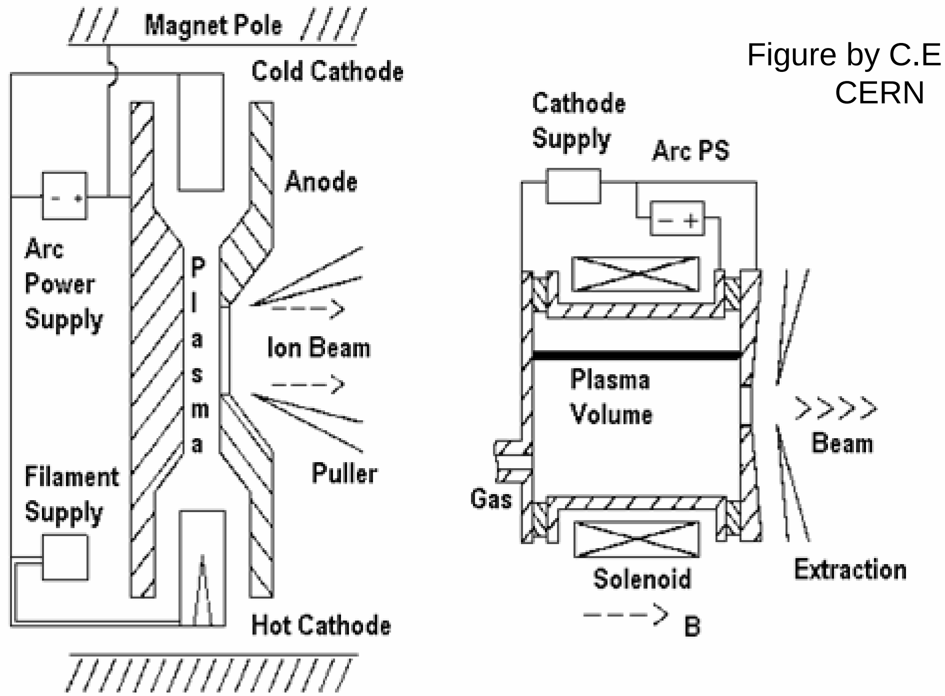


Fig. 3 Schematic hot cathode Penning

Fig. 4 Axial extraction Magnetron

Figure by C.E. Hill
CERN

The arc electric field accelerates the electrons and a magnetic field makes them move on spiraling orbits inside the plasma ionizing more atom along their trajectory.

The ions then diffuse out from an aperture on the plasma chamber and are accelerated by the voltage between cathode and anode.

ECR Sources

- **Non-relativistic particles in a constant magnetic field move on a circular trajectory at a <u>constant revolution frequency</u> independently from their energy (cyclotron principle):**

$$\omega_0 = \frac{eB}{m}$$

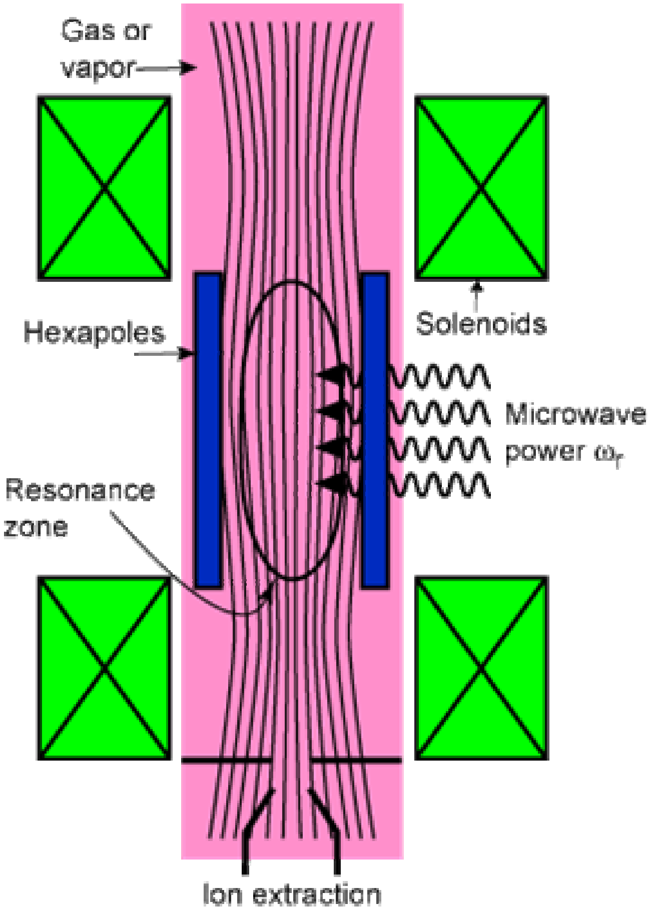


Figure by NSCL- Michigan State University

- **Let's consider a plasma immersed in a solenoidal field. Applying an electromagnetic field with frequency ω_0, the electrons in the plasma will resonate at their cyclotron frequency gaining energy from the field.**

- **The electrons will describe spiraling orbits with increasing radius and ionizing additional atoms along their path.**

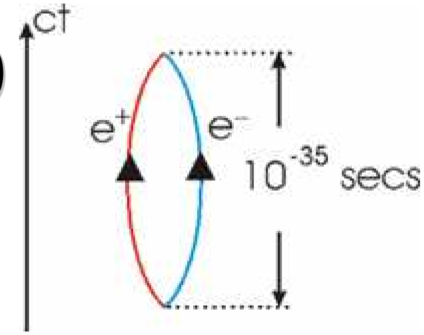
- **Electron Cyclotron Resonance (ECR) sources, exploit this mechanism.**
In such sources there is no cathode and the average lifetime and reliability is very good.

Negative Ion Sources

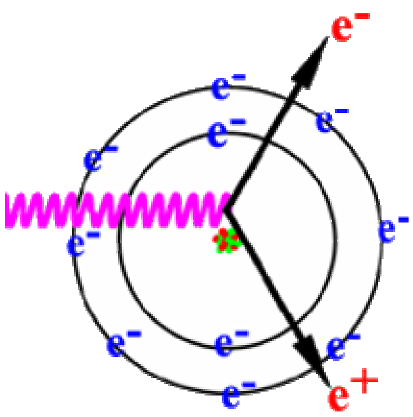
- The same schemes described for positive ions generation can be used for generating negative ions, (penning, magnetrons, …).
- The physical processes in negative ion sources are still poorly understood but three types of source are generally recognized; surface, volume and charge exchange.
- In a *surface source*, ~ a mono-layer of Cesium on the source surface strongly increase the production of H^-. Collision of the plasma particles with the Cs surface generates desorption of ions including the desired H-.
- In *Volume Sources*, scattering between the gas molecules can generate negative ions. For example, measurements of H^- ions in large-volume, low-pressure hydrogen discharges indicated densities which were much larger than those predicted by theory.
- *Double charge exchange* of positive (or neutral) ion beams on alkali metal vapor targets was once a favored method of negative ion production. They are not very efficient in producing high energy H^- but are still very useful for producing "exotic" species of negative ions.
- Negative ions find very important applications in Tandems and in injecting into accumulator rings by stripping the charge: the process is non-hamiltonian and the beam emittance can be reduced.

Positron Sources

• From quantum field theory, a photon with energy larger than twice the electron rest mass (~1.02 MeV) "oscillates" between the phase of photon and the one of *pair of virtual electron and positron*. This virtual particles live for an extremely short time for then recombining back into the original photon ready for a new cycle to start again.



• This is a consequence of the Heisemberg indeterminacy principle and these virtual particles cannot be directly detected.



• Anyway, if the photon during this "virtual particle phase" passes close to an atom nucleus, the interaction between the nucleus fields and the pair will allow for the virtual particles to become real and separate from each other.

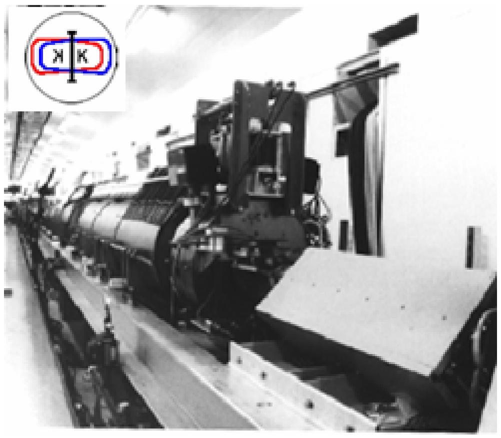
Positron Sources

• In existing positron sources, the high energy photons required for pair production are generated by first impinging a high current electron beam on a high Z metallic target.

• The electrons penetrating the material are deflected by the nuclei fields and radiate high energy photons. These photons interact with the nuclei finally generating the pairs.

• The newborn positrons leaving the target are separated from the electrons, captured and accelerated to higher energies in a dedicated section of the linac optimized for the task.

DAΦNE
The Frascati Φ-factory



Current at the positron converter (PC)	**> 4 A**
Energy at the PC	**250 MeV**
Beam size @ the PC	**1 mm r.m.s.**
Positron current at the Linac end (550 MeV)	**100 mA**

Antiproton Sources

• **Existing sources of antiprotons (Fermilab and CERN) exploit the proton-antiproton pair production mechanism when high energy protons scatters on the nuclei of a metallic target generating pairs.**

Production rate is very small:
~ 10^{-5} antiproton/proton
~ 10^{11} antiproton/hour

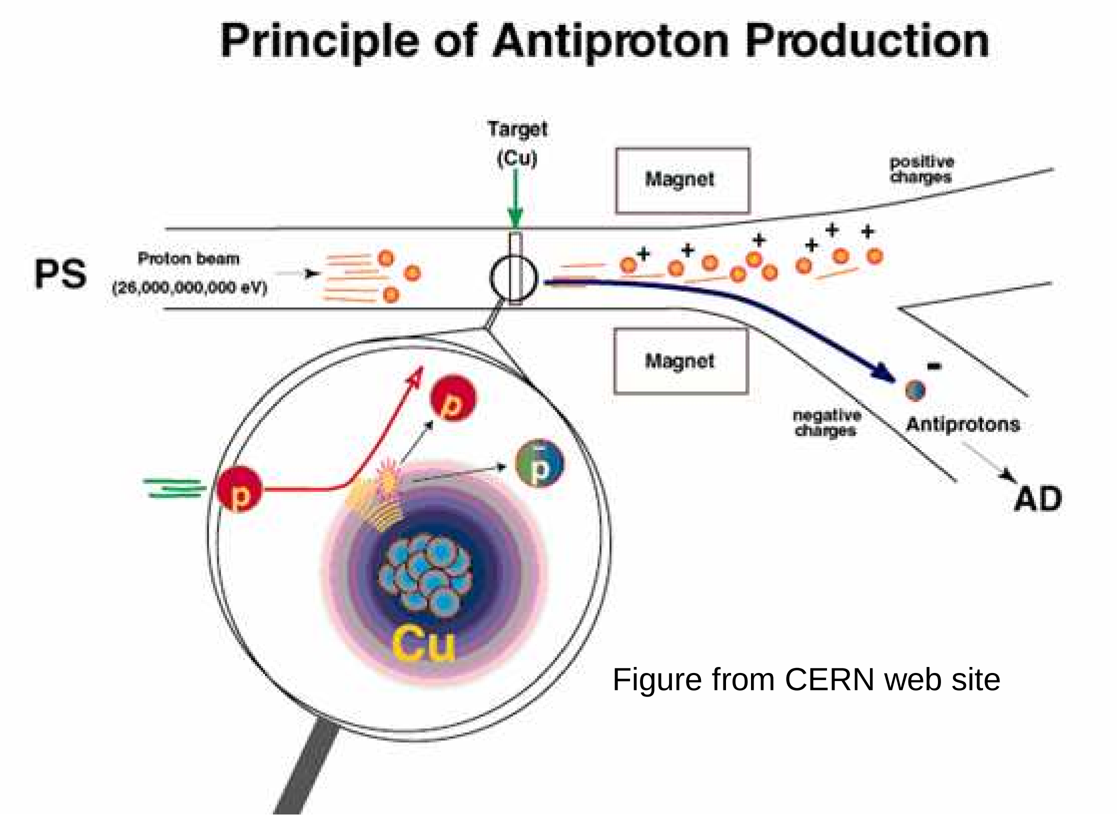
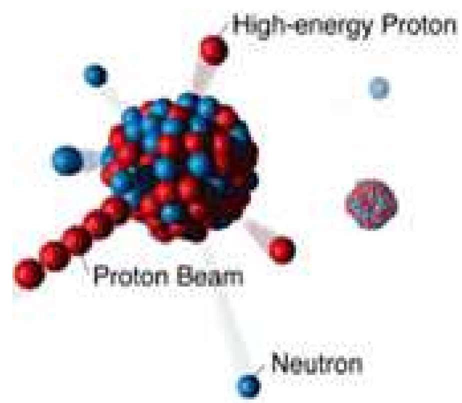


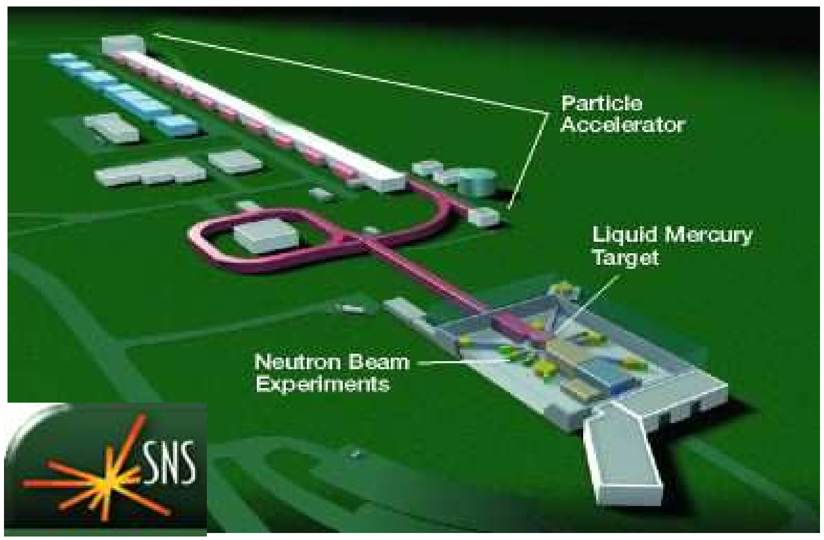
Figure from CERN web site

Neutron Sources

• The more efficient neutron sources are nuclear reactors. However, they cannot be built because international treaties prohibits civilian use of highly enriched uranium U_{235}.

• An alternative scheme fo generating neutrons is given by the so-called **spallation neutron source**, where a high energy-high power accelerator produces pulsed neutron beams by bombarding a target with intense proton beams.





1 GeV Protons at target
1.4 MW Proton Power at the Target
24 kJ/pulse
1.5 x 10^{14} protons /pulse

> 1.5 G$

Possible Homework

• **Calculate the RF frequency for an ECR H^+ source with a solenoidal field of 0.5 T.**

• **Calculate the minimum energy in eV units that a photon should have to potentially generate a proton-antiproton pair.**

• **Estimate the number of hours required to store 100 mA of antiprotons in the Tevatron at the Fermilab. The ring circumference is ~ 6400 m, the beam energy is 980 GeV. Assume an injection rate of about 6.5×10^{11} antiprotons/hour. Remember that the antiproton mass is ~ 1.6726×10^{-27} kg.**